PD Properties and Gases Generated by Palm Fatty Acids Esters (PFAE) Oil

by Abdul Rajab

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***Abstract*— Partial discharge properties and gas generation of palm fatty acid ester (PFAE) oil of various moisture content levels are investigated under AC high voltage utilizing needle plane electrode configuration. Partial discharge inception voltage (PDIV) at various oil sample conditions are discussed. Variations of PD magnitude and PD number against voltage application change are analyzed. The effects of moisture content on PD properties and generated combustible gases of PFAE are also elaborated.**

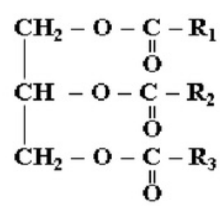
Keywords*— dissolved gas analisis, ester oil, moisture content, partial discharge, transformer.

I. Introduction

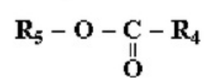
The development and practical use of environmentally friendly insulating oil from natural ester or vegetable oils caught serious attention of many researchers during the last two decades. The oils have high rate of biodegradability, which is the important factor to be considered as environmentally friendly fluid. In addition, natural ester (vegetable) oils also possess higher flash point and fire point, thus lower fire risk, compare to that of mineral, which is the most widely used insulating oil in electrical apparatus like transformer until now. Though their cooling properties are poorer than those of mineral oil, the natural ester oils are widely adopted in transformers over the world due to their advantages mentioned above [1]. Natural ester oil based insulating liquid was used in medium voltage of distribution transformer for the first time in 1996, and then followed by their application in high voltage of power transformer in 2002 [2]. The natural esters that have been successfully implemented in transformers are of triglyceride form, which is the original structure of the oils.

Following the successful application of natural ester of triglyceride type as insulation liquid in transformer, natural ester of mono ester type was introduced for the same purpose. Fig. 1(a) and 1(b) give chemical structures of natural esters, both triglyceride and mono ester types, respectively [3, 4]. Changing the molecular structure from triglyceride to mono ester is proven to significantly reduce the viscosity of natural esters, thus improving their fluidity and cooling properties. The proper selection of R_4 and R_5 (see Fig. 1(b)) further improves the fluidity of the natural mono esters. As the result, the viscosity of PFAE is even lower than the typical viscosity value of mineral oil. The viscosities of triglyceride type natural ester based insulation oil, the mono ester type one, and mineral oil are 33, 5.1 and 9.2 cSt, respectively [4, 5].

Since PD detection is an important method of early warning of deterioration of insulation, PD properties of PFAE need to be investigated. This is the motivation of the work presented in this paper. PD properties and generated combustible gases by PD in PFAE are investigated. Partial discharge inception voltage (PDIV) at various oil sample conditions are discussed. Variations of PD magnitude and PD number against voltage application change are analyzed. The effects of moisture content up to 188 ppm or about 17% relative moisture content on PD properties and generated combustible gases of PFAE are also elaborated.



(a) Triglyceride (Tri ester)



(b) Mono ester

Fig. 1. Chemical structures of natural esters

II. Experiment

A. Samples

Sample used in the experiment was palm fatty acid ester (PFAE), which is developed to be used for oil filled transformer. Three kinds of oil samples with different moisture content were prepared by mixing degassed oils and non-degassed oils with the percentage of 100:0 %, 50:50 %, and 0:100 %. The results are oil samples having three different moisture content levels, which were 102, 144, and 188 ppm, respectively.

B. *Experimental Arrangement and Procedure*

Partial discharge was generated in each oil sample by applying AC high voltage on electrode pairs of needle plane configuration. The schematic view of electrode configuration is shown in Fig. 2. The needle having tip radius of 10 μm was used in conjunction with a plane electrode having diameter and thickness of 68 mm and 5 mm, respectively. With an acrylic of 5 mm thick on the plane electrode surface, the gap between the needle and acrylic was 5 mm. Application of voltage was started at 7 kV, and it was increased with the increment of 1 kV up to 21 kV. PD pulses were detected using RC integrated circuit, and PD measurement was conducted for 2 minutes at each voltage level using an oscilloscope (Tektronix, DPO 7504 type) as shown in Fig. 3.

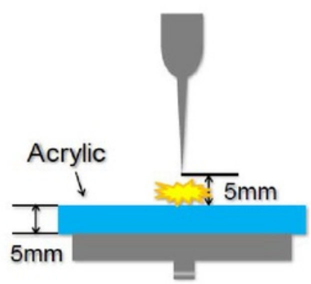


Fig. 2. Schematic view of needle plane electrodes configuration, an acrylic of 5 mm in thickness was put on the plane electrode

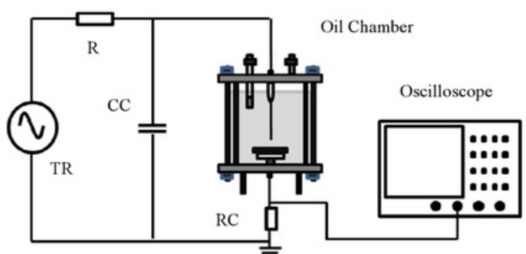


Fig. 3. Experimental set up

To generate enough amounts of combustible gases in oil sample, an AC voltage of 20 kV was applied to the needle electrode immersed in oil sample until PD number of 8000 took place in oil. This procedure was conducted for all oil samples having three different levels of moisture content.

Two gas samples were prepared for gas analysis. The first one was taken from gas part, the oil-free space on the upper part of the chamber, whereas another one was taken from the oil part. Dissolved gas in the oil was extracted using head space method. Gas samples were then analyzed using a gas chromatography (Shimazu Corp. Japan, GC-2014 model).

III. Experimental Results and Discussion

A. *PD Properties*

In this paper partial discharge inception voltage (PDIV) is defined as the lowest applied voltage at which the first PD with the magnitude of equal or greater than 100 pC, according to IEC61294, takes place. Using this definition, then PDIV of three different oil samples having moisture content levels of 102, 144, and 188 ppm are 12, 10, and 12 kV, respectively, as listed in Table I. These PDIV levels seem to be independent on the moisture content levels. The 10 kV PDIV of oil sample containing moisture of 144 ppm is more likely to be due to the existence of a small bubble, created during the oil filling process, which was failed to be completely removed.

TABLE I. PDIV of PFAE Samples of Different Moisture Content

Moisture Content (ppm)	PDIV (kV)
102	12
144	10
188	12

Fig. 4 and 5 show PD number and average PD charge as a function of applied voltage, respectively. As can be seen in these Fig., both PD number and average PD charge increase with the applied voltage. No significant difference in PD properties appear for PFAE samples of three different moisture content levels. The result indicates that PD took place in the similar way to the occurrence of total breakdown in the insulating oil. Namely, it is reported that moisture content up to 300 ppm does not cause a decrease in breakdown voltage (BDV) of natural ester [2]. It should be noticed that relative moisture content is more useful than actual moisture content. The relative moisture content up to about 10% and 30% of unclean and clean insulation oils, respectively, do not significantly affect the breakdown voltage of oils, irrespective to oil type [2]. Fig. 6 shows breakdown voltage of several oil types as a function of relative moisture content [2].

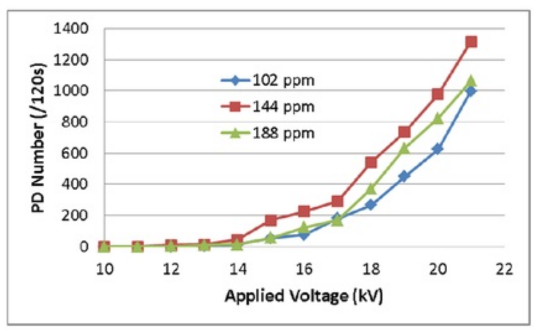


Fig. 4. Relationship between PD number and applied voltage for 2 minutes in PFAE of different moisture content

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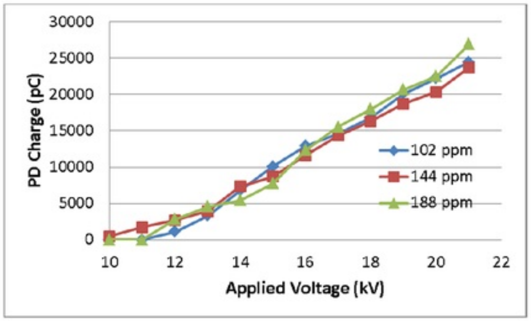

Fig. 5. Relationship between PD charge and applied voltage for 2 minutes in PFAE of different moisture content.

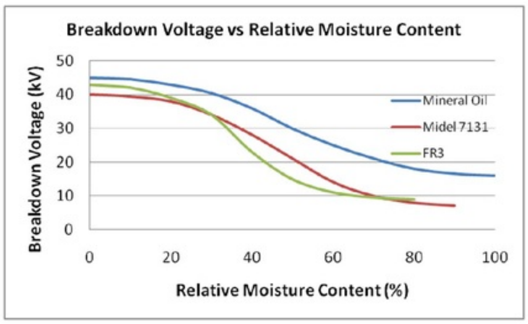

Fig. 6. Breakdown voltage of several oil types as function of relative moisture content. The graph was reproduced form [2].

Since the oil samples were filtered before being subjected to PD, they were considered to be clean oil. With the moisture solubility of PFAE at room temperature is 1100 ppm (assumed), the largest relative moisture content of tested sample is about 17%. It is then reasonable to state that the variation of moisture content up to 188 pm, or about 17% relative moisture content, do not have significant effect on PD properties of PFAE.

B. Generated Combustible Gases

The types of combustible gases generated by 8000 number of PD, stressed at 20 kV under the needle plane electrode configuration, in PFAE samples of three different moisture content levels are methane, ethylene, acetylene, and carbon monoxide, as depicted in Fig. 7. It is interesting that methane is dominant gas produced by the oils for all moisture content levels. Ethane, on the other hand, was not found in all oils samples. Carbon monoxide, which is expected to be generated in higher amount due to the existence of –COO- link in PFAE's structure, was found to be even lower than the amount of generated ethylene.

Another interesting point that can be drawn from Fig. 7 is that hydrogen is produced by PFAE oil in not significant amount, and this behavior applies for all tested samples with different levels of moisture content. These results differ from those usually found in mineral oil under PD stress. It is well known that hydrogen is the key gas indicating the presence of PD stress in mineral oil. Hydrogen was also reported to be dominant in concentration found in a vegetable oil based insulating liquid of triglyceride type, FR3, under PD stresses [6].

Our results are similar in tendency, except ethane generation, to those reported in [7], but quite distinct from those in [8], although the samples used in our experiment and experimental conditions have a lot of similarities to those in [7] and [8]. Fig. 8 shows combustible gases generated by various natural monoester and mineral oil, reproduced from [7] and [8]. PFAE (used in our experiment and in [7]), Pastell 2H-08 (used in [7] and [8], and Pastell M12 (used in [8]) are of natural mono ester type (see Fig. 1(a)), and they do not have C=C double bond in their hydrocarbon chains. Therefore, they possess exactly the same chemical structure. Moreover, all oil types are derived from the same source, palm oil. All sample oils were stressed by PD under AC high voltage utilizing needle-plane electrode configuration. The only significant difference to be noted is the applied voltage levels being experienced by the oils during the PD stresses. Applied voltage level in our case was 20 kV, whereas those in [7] and [8] are 17 and 25 kV, respectively. This applied voltage difference might be responsible for the difference in gas generation mentioned above. The higher applied voltage, the higher energy dissipated by the discharge, thus produce the higher temperature of oil at the discharge path.

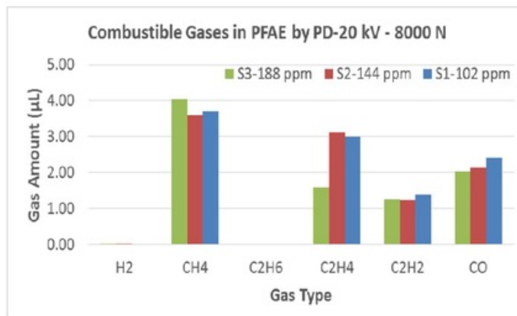

Fig. 7. Generated combustible gases in PFAE samples of different moisture content levels by PD at 20 kV with PD number of 8000.

The average magnitude of 8000 number of PD pulses detected in PFAE samples with three different moisture content levels, are listed in Table II. The amount of generated combustible gases per PD magnitude is shown in Fig. 9. No consistent tendency about the dependency of generated combustible gases on the change of moisture content of PFAE can be seen in Fig. 9. However, the increase in number of PD greatly influence the amount of generated combustible gases except methane, as depicted in Fig. 10.

TABLE II. PD CHARGE OF PFAE SAMPLES OF DIFFERENT MOISTURE CONTENT LEVELS

Moisture Content (ppm)	PD Charge (pC)		
	Min	Max	Average
102	2408	42691	24539
144	1532	42691	21840
188	1970	39188	22659

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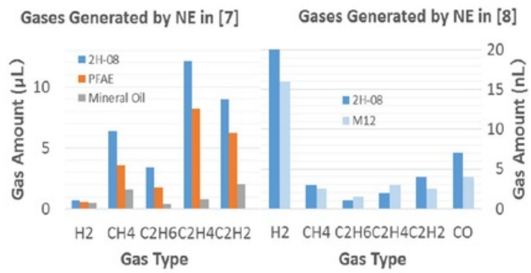

Fig. 8. Generated combustible gases by PD at 17 and 25 kV in various natural mono esters and mineral oil. The graph was reproduced from [7] and [8].

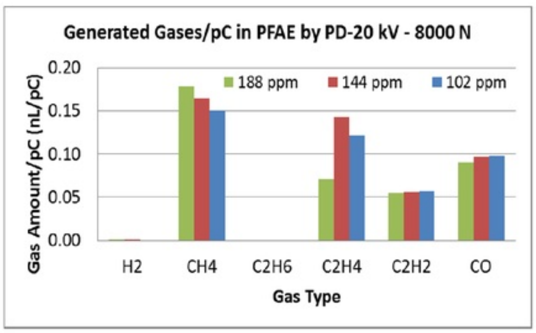

Fig. 9. Generated combustible gases/pC in PFAE samples of different moisture content levels by PD at 20 kV with PD number of 8000

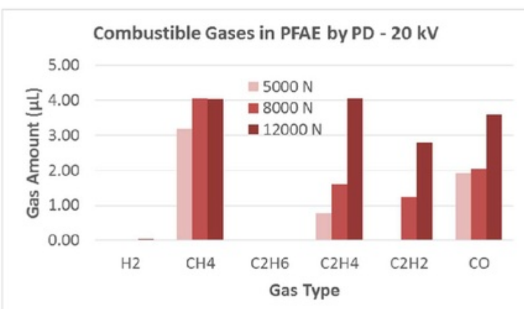

Fig. 10. Generated combustible gases by PD at 20 kV under different PD number in three PFAE samples having relatively constant moisture content

IV. CONCLUSSIONS

We have studied PD properties and gases generated by PFAE under various levels of moisture content up to 188 ppm or about 17% relative moisture content. Some conclusions can be made as follows:

1. PD properties of PFAE such PDIV, PD charge and PD number seem to be independent of moisture content up to 188 ppm or about 17 % relative moisture content.
2. It is indicative that moisture content affects PD activities of oil in the way similar to the breakdown event.
3. Variation of moisture content does not cause a significant difference in generated combustible gases, but the variation of PD number does.
4. The tendency of generated combustible gases is changed as the applied voltage change. It could be due to the different temperature levels resulted by discharge at different voltage levels.

ACKNOWLEDGMENT

Abdul Rajab would like to thank DG-RSTHE of Indonesian Government for providing doctoral scholarship.

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